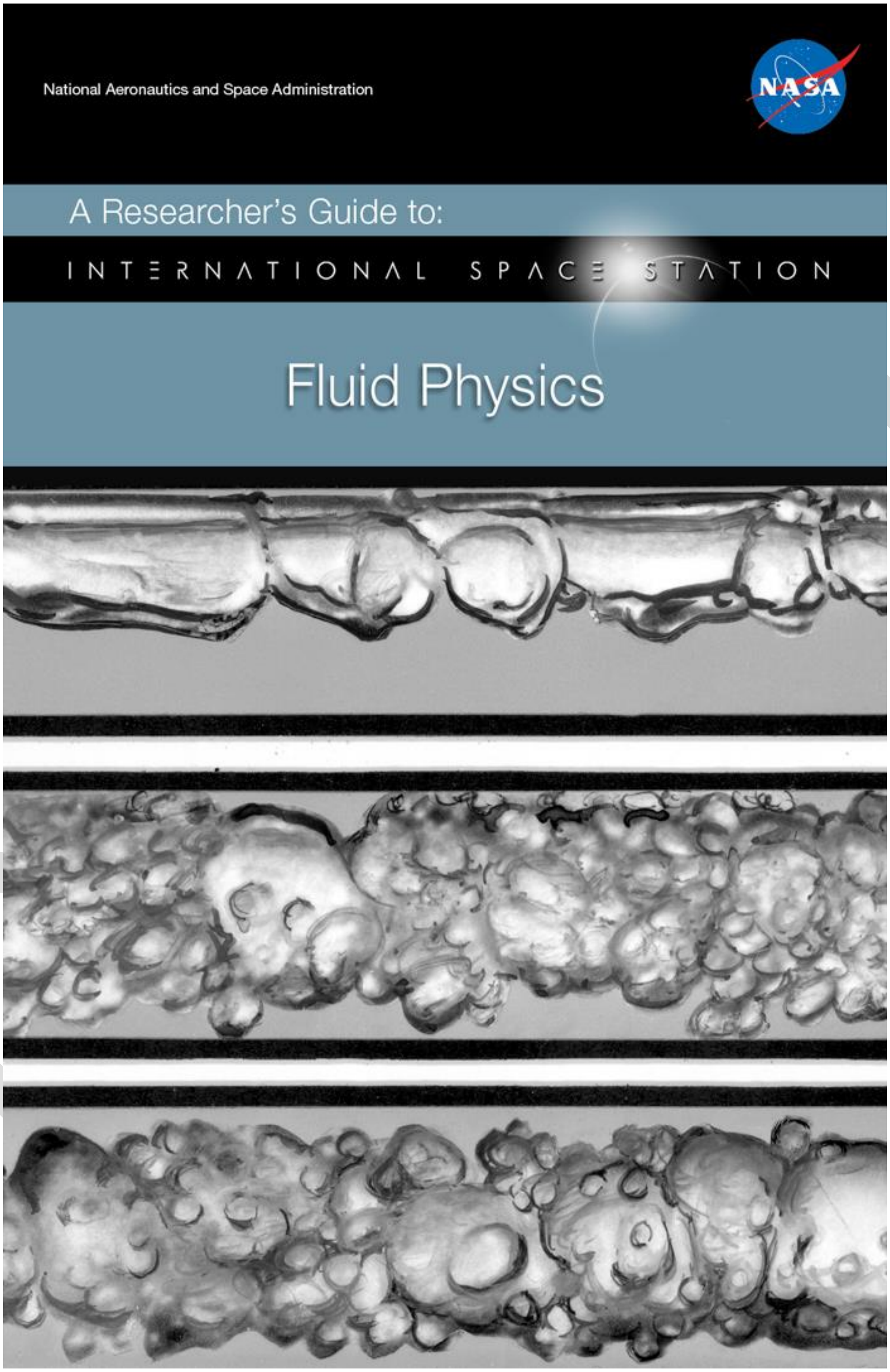
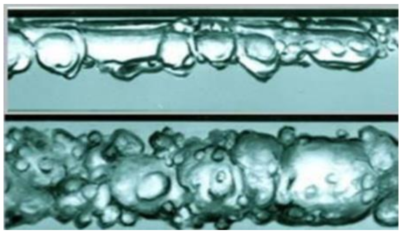
FLUID PHYSICS

***** DRAFT *****





Prepared by

Dr. David F. Chao*

Dr. Robert D. Green*

John B. McQuillen*

Dr. William V. Meyer**

Dr. Brian J. Motil*

*Fluids Physics and Transport Branch, NASA's Glenn Research Center, Ohio 44135

**National Center for Space Exploration Research of Fluids and Combustion, NASA's Glenn Research Center, Ohio 44135

Table of Contents

2 Why use the International Space Station (ISS) as a Laboratory?

A fluid is any material that flows in response to an applied force; thus, both liquids and gases are fluids. Nearly all of the life support, environmental and biological, processes take place in the fluid phase. Fluid motion accounts for most transport and mixing in both natural and man-made processes as well as within all living organisms. Fluid physics is the study of the motions of liquids and gases and the associated transport of mass, momentum and energy. The need for a better understanding of fluid behavior has created a vigorous, multidisciplinary research community whose ongoing vitality is marked by the continuous emergence of new fields in both basic and applied science. In particular, the low-gravity environment offers a unique opportunity for the study of fluid physics and transport phenomena. The nearly weightless conditions allow researchers to observe and control fluid phenomena in ways that are not possible on Earth.

Experiments conducted in space have yielded rich results. Some were unexpected and most could not be observed in Earth-based labs. These results provided valuable insights into fundamental fluid behavior that apply to both terrestrial and space environments. In addition, research on fluid management and heat transfer for both propulsion and life-support systems, have contributed greatly to U.S. leadership in space exploration.

Much is still unknown or not fully understood. In order to design for the human or robotic exploration of space and other planetary environments, it is necessary to understand how engineering and fluid systems perform in the near-weightless environment experienced in reduced gravity environments found on the moon or Mars or during space travel.

The difference in the behavior of fluid systems in space or on other planetary bodies can be attributed primarily to buoyancy. The near elimination of buoyancy and sedimentation within inhomogeneous fluids in the low-gravity environment provided by the International Space Station (ISS) allows scientists to study the behavior of a whole range of fluids. While these conditions can be achieved in free-fall facilities, such as drop-towers and aircraft, the limited duration of these tests is insufficient for fluids experiments that require minutes, hours or even days to be performed successfully.

The Fluid Physics discipline, which focuses on gravity-related research issues, includes complex fluids, multiphase flow and heat transfer, and interfacial phenomena (including capillary flow).

3. Results from past research of Fluid Physics in Space

Gravity strongly affects fluid behavior by creating forces that drive motion, shape phase boundaries and compress gases. One significant gravity-driven motion is buoyancy-induced flow in which lighter, less dense molecules flow upwards while denser molecules flow down. An example of this type of flow can be found in boiling water in which heated steam bubbles rise up as cooler, and denser water flows down. Sedimentation is a similar gravity-driven phenomenon. In microgravity, the effects of the gravity-driven processes of sedimentation and buoyancy-induced flow are nearly eliminated. The absence of these phenomena allows scientists to observe other phenomena that are present under the influence of Earth's gravity but usually obscured.

3.1 Complex Fluids

Complex fluids include non-Newtonian fluids, colloids, polymers, foams, microemulsions, gels, granular materials, and a number of biological materials such as proteins, biomembranes and cells. These materials share an important common feature in that predominant physical behaviors occur at an energy scale comparable with that of room temperature thermal energy. Recognized as condensed matter physics at liquid phases, complex fluids comprise a large class of materials ranging in sizes from sub nanometer to micron scales with their physical properties determined by the interplay of entropic and structural intermolecular forces and interfacial interactions. Soft condensed matter comprises a variety of physical states that are easily deformed by thermal stresses or thermal fluctuations and studied at different forms at the fluid state such as foams, emulsions, colloids, monolayers, freely suspended thin fluid films, gels, and biofluids such as biomembranes and cells. The study of complex fluids encompasses diverse fields such as phase transitions, nucleation and crystal growth, glass formation, chaos, field theory, and much more. Furthermore, research in complex fluids provides the underpinnings of applications related to NASA exploration of planetary surfaces as well as terrestrial applications in industries such as pharmaceutical, chemical, plastics, petroleum, electronics and liquid-crystals. According to the National Research Council Decadal (2011) Report, these industries contribute over $1 trillion annually to U.S. manufacturing output. The need to conduct research in a microgravity environment is very clear. Because of the relatively large size of the basic structures, gravitational forces dominate and cause sedimentation, particle jamming, convective flows and other induced gradients obscuring weaker forces such as surface tension and entropic forces. In granular materials, stresses and yield properties are also sensitive to gravity.

Prior to the ISS, a series of microgravity experiments were flown that yielded many new and interesting results. Some of the early experiments included Colloidal Disorder-Order Transition, Colloidal Gellation-2, and Physics of Hard Spheres, all flown on the space shuttle. They revealed the first observations of dendritic growth in hard-sphere colloidal systems. Research results established that colloidal samples remaining in a glassy phase on Earth (i.e., do not crystallize on Earth), become ordered (i.e., crystallize) in microgravity.

On the ISS, the Physics of Colloids in Space (PCS) experiment studied the phase behavior, growth dynamics, morphology and mechanical properties of different types of colloidal suspensions including binary colloidal alloys (Figure 3.1-1), colloidal polymer mixtures, fractal colloidal aggregates, and the natural entropy driven transition from a disordered glassy state to an ordered crystalline one (Figure 3.1-2).

The Binary Colloidal Alloy Tests (BCAT)-3/4/5/6 experiments were a set of notebook-size science investigations that contained 10 samples each. Once in the microgravity environment aboard the ISS, these samples were individually mixed until their structure was randomized and subsequently photographed as the structures evolved. Many different types of science were addressed.

The BCAT experiments on seeded growth showed that glassy (completely disorder) samples will crystallize differently in the absence of gravitational sedimentation and jamming as shown in Figure 3.1-3. The use of seed particles have been predicted to cause heterogeneous nucleation (many different crystals) rather than large homogeneous crystals.

Another theme in the BCAT experiment is the study of phase separation with model-critical fluid samples on the ISS. These model systems do not require the micro-Kelvin temperature control of traditional critical fluids. They serve as a model system for understanding ideal systems formed from same-size (monodisperse) particles whose attractive force can be adjusted by the addition of a polymer. Depletion attraction is used to set the effective attractive force between particles.

From these studies, it was found that the critical point is not where the literature predicts (literature based on observing phase separation in the presence of gravity). True microgravity environments are needed to probe this physics.

The competition between a phase-separation process and an order-disorder transition remains largely unstudied. New BCAT measurements capturing the arrest of phase separation by crystallization are the focus of the “Compete” Samples. Improved understanding of these processes will lead to more refined manufacturing processes and commercial products. Some exciting and pleasantly surprising results are shown in Figure 3.1-4.

Magnetorheological (MR) fluids are suspensions of small (micron-sized) superparamagnetic particles in a nonmagnetic medium. These controllable fluids can quickly transition into a nearly solid-like state when exposed to a magnetic field and return to their original liquid state when the magnetic field is removed. Their rheological properties (how they deform and flow) can be controlled by manipulating the strength of the magnetic field. Because of the rapid-response that can be achieved between mechanical components and electronic controls, MR fluids can be used to improve or develop new brake systems, seat suspensions, robotics, clutches, and airplane landing gear.

The Investigating the Structures of Paramagnetic Aggregates from Colloidal Emulsions investigation studied the fundamental behavior of MR fluids under the application of constant and pulsed magnetic fields. Observations of the microscopic structures yielded a better understanding of the interplay of magnetic, surface and repulsion forces between structures in these fluids. These fluids are classified as smart materials because they transition to a solid-like state by the formation and cross-linking of microstructures in the presence of a magnetic field. On Earth, these materials are used for vibration dampening systems that can be activated as needed. This technology shows promise for designing structures such as bridges and buildings that can better tolerate earthquake damage.

The Shear History Extensional Rheology Experiment was designed to investigate the effect of preshearing (rotation) on the stress and strain response of a polymer fluid (a complex fluid containing long chains of polymer molecules) being stretched in microgravity. This information is particularly relevant for understanding the deformation and evolution of non-Newtonian thin fluid columns (threads) in a wide variety of industrial processes such as fiber spinning, film coating, enhanced oil recovery, injection molding, drag reduction for advanced aircraft, boats and submarines, or food and consumer product processing. In fiber spinning, the fluid experiences a complex transient shear deformation as it flows through the spinneret before it is stretched axially. Additionally, a fundamental understanding and measurement of the extensional rheology of complex fluids is important for understanding stability and breakup of jets and containerless processing. It is an important operation for fabrication of parts, such as adhesives or fillers, using elastomeric materials on future exploration missions.

In a microgravity environment, there is a large increase in the radial dimension of the initial liquid bridge because of the absence of gravitational body forces. By increasing the initial radius, the viscous force is increased and the time evolution of the tensile force becomes slow enough to be measurable for extended times permitting the long dynamics of the filament thinning to be monitored. A stable microgravity environment enables the understanding of the effect of the initial conditions on capillary thinning and time to breakup.

Foams are dispersions of gas into liquid or solid matrices. They are typically manufactured under conditions where the matrix is liquid. For solid foams, the matrix is solidified afterwards. The behavior of foams in microgravity and on Earth are very different because liquid drainage does not occur in microgravity conditions. Drainage is the irreversible flow of liquid through the foam leading to the accumulation of liquid at the foam bottom and to a decrease of global liquid content within the foam; in this case, the gas bubbles conform to the polyhedra in the upper portion of the foam creating the so-called "dry foam." When the liquid films between the bubbles become very thin, they break, collapsing the foam. This happens when suitable stabilizing agents (well-chosen surfactants or solid particles for aqueous foams) are absent. Microgravity offers the opportunity to investigate the so-called "wet" foams, which cannot be stabilized on Earth because of drainage. Drainage becomes faster as the foams get wetter. Theoretical approaches of drainage rely on assumptions that are only valid for dry foams. New behaviors or regimes are expected to exist for wet foams; however, they are masked by convective instabilities on Earth. The elastic and viscous properties of wet foams are also expected to be strongly modified by the presence of solid particles. The Foam Optics And Mechanics (FOAM) project aims at the study of aqueous and non-aqueous foams in the microgravity environment aboard the ISS. The FOAM project is divided in two experiments: “FOAM coarsening” and “FOAM stability.” The objective of FOAM coarsening is the study of the quiescent coarsening of foams as a function of the liquid fraction.

3.2 Multiphase Flow and Heat Transfer

This research area, which has applications in the engineering of heat transfer system and gas purification systems, focuses on complex problems of two-phase fluid flow. Scientists are seeking to understand how gravity-dependent processes, such as boiling and steam condensation, occur in microgravity. Boiling is known to be an efficient way to transfer heat, and it is often used for cooling and energy conversion systems. In space applications, boiling is preferable to other types of energy conversion systems because it is efficient and the apparatus needed to generate power is smaller. Another of the mechanisms by which energy and matter (atoms, molecules, particles, etc.) move through liquids and gases, is diffusive transport. The way atoms and molecules diffuse through a liquid or gas is due primarily to differences in concentration or temperature. Researchers use microgravity to study diffusion in complex systems, a process that would normally be eclipsed by the force of gravity. Understanding the physics of multiphase flow and heat transfer in space will enhance the ability of engineers to solve problems on Earth as well. Potential applications of this research include more effective air conditioning and refrigeration systems, and more efficient power-generating plants.

During the past 20 years, three multiphase flow experiments were conducted aboard the space shuttle, and two were conducted aboard the ISS.

The Vented Tank Resupply Experiment (VTRE) was conducted to test improved methods for in-space refueling. VTRE used vane Propellant Management Devices (PMD) to separate the liquid and gas phases of Refrigerant 113 in low gravity. Experiment objectives included testing the capability of the vane PMD to retain liquid during transfer between the two tanks, liquid-free venting of pressure, and recovery of liquid into the PMD after a thruster firing.

The Tank Passive Control Experiment also used Refrigerant 113 to demonstrate the effectiveness of a low-velocity axial jet to mix the fluid and thereby control its pressure. Pressure increases of the volatile fluid were induced with heaters, simulating the in-space storage of a cryogenic fluid. Pressure control was found to be effective and repeatable at both high- and low-fluid fill levels over a wide range of jet velocities with varying amounts of noncondensible gases in the ullage, a variety of liquid/vapor orientations, acceleration environments, heat inputs, and with and without ullage penetration by the jet. Pressure spikes caused by explosive boiling were sometimes observed during heating at low-heat fluxes but were controllable with gentle mixing.

The Pool Boiling Experiments (PBE) conditioned liquid (R-113) to an initial, precisely defined pressure and temperature and subjected the liquid to a step-imposed heat flux from a semi-transparent, thin-film heater to initiate and maintain boiling for a defined period of time at a constant pressure level. Transient measurements of the heater surface and fluid temperatures near the surface were made, and two simultaneous views from beneath the heating surface and from the side were recorded.

Several modes for propagation of boiling across the heater surface and subsequent vapor bubble growth were observed. Of particular interest were the extremely dynamic or "explosive" growths, which were the result of the large increase in the liquid-vapor interface area associated with the appearance of a wavy interface, which itself is due to the presence of an instability. Small vapor bubbles migrated toward and coalesced with a larger bubble at the combination of the lower heat flux levels and highest subcooling levels. This phenomenon enhanced the heat transfer by approximately 30 percent.

More recently, the Boiling eXperiment Facility used normal perfluorohexane to conduct two experiments on the ISS: The Microheater Array Boiling Experiment (MABE) and the Nucleate Pool Boiling eXperiment (NPBX).
MABE used an array of 96 transparent individually controlled microheaters to perform experiments over a wide range of heater and liquid temperatures, pressures and heater sizes. Experiments have revealed two regimes for predicting pool-boiling behavior: Buoyancy Dominated Boiling (BDB) and Surface tension Dominated Boiling. Within the BDB regime, as the vapor bubble grows larger the density difference between the vapor bubble and surrounding liquid causes gravity to push the bubble off the heater surface and rise through the liquid. Liquid rushes in behind the bubble and the process of heating and boiling repeats. This behavior has been observed for a wide range of acceleration (gravity) levels ranging from high gravity (>1 g) to less than lunar gravity (1/6 g). At lower gravity levels, the boiling behavior is controlled by surface tension whereby a bubble covers a large portion of the total heater surface. Its growth is fed both by vaporization of liquid and merging with smaller vapor bubbles that surround the large bubble. Its size is limited by condensation on the bubble surface in cooler liquid away from the heater.

Based on the high-quality microgravity data (a/g<0.000001), a gravity scaling parameter for heat flux was modified to account for these ISS results, which was primarily based on parabolic aircraft flight experiments (a/g~0.01). While the aircraft flights were instrumental in developing the model, residual fluctuations on the aircraft significantly affected the boiling behavior, which is why the ISS environment was critical.

The robustness of this framework in predicting low-gravity heat transfer is further demonstrated by predicting many of the trends in the pool-boiling literature for several different fluids over a range of heater sizes, gravity levels, and those that previously could not be explained by any single model.

NPBX used a polished aluminum disc heated by strain gage heaters. Four cylindrical cavities were located at the corners of a square with a fifth cavity in the middle. The results of the experiments showed that a single bubble continues to grow to occupy the size of the chamber without departing from the heater surface. During lateral merger of bubbles at high superheats (the difference between the heater and liquid temperature), a large bubble may lift off from the surface but continue to hover near the surface. Neighboring bubbles are continuously pulled into the large bubble. At smaller temperature differences, bubbles at neighboring sites simply merge to yield a larger bubble. The larger bubble mostly positioned itself in the middle of the heated surface and served as a vapor sink. The latter mode persisted when boiling was occurring all over the heater surface. Heat fluxes for steady-state nucleate boiling and critical heat fluxes were found to be much lower than those obtained under 1 g, that is normal Earth gravity conditions.

3.3 Interfacial Phenomena/Capillary Flow

Fluid dynamics, instabilities and interfacial or capillary flow are another very important subset of fluid physics. Capillary flows and phenomena are applicable to a myriad of fluids management systems in low-g including fuel and cryogen storage systems, thermal control systems (e.g., vapor/liquid separation), life support systems (e.g., water recycling), and materials processing. In fact, NASA's near-term exploration missions plan larger liquid propellant tanks than have ever flown for interplanetary missions. Under microgravity conditions, capillary forces can be exploited to control fluid orientation so that such large mission-critical systems perform predictably.

Interfacial phenomena are driven by the surface tension fluid property and the contact angle, or degree of wetting, which is dependent on both fluid and the adjoining surface. Capillary forces are masked by the gravitational force exerted on fluids, hence the need to study under low-gravity conditions. Because hydrostatic pressure is absent in microgravity, technologies for liquid management in space use capillary forces to position and transport liquids. On Earth, the effect of capillary forces is limited to a few millimeters. In space, these forces still affect free surfaces that extend over meters. For the application of open channels in propellant tanks of spacecraft, design knowledge of the limitations of open capillary channel flow is a requirement. These limitations are based on the restriction that the liquid fuel must be free of bubbles prior to entering the thrusters.

Early drop tower experiments established the need to understand the effects of interfacial phenomena in a microgravity environment. The first spaceflight microgravity experiment was an interfacial phenomena investigation performed by astronaut Scott Carpenter on Mercury flight MA-07 in 1962. In particular, it tested fluid equilibrium configurations in a cylindrical-baffle-in-a-sphere geometry.

Recent experiments flown on the ISS include the Capillary Flow Experiments (CFE-1, CFE-2) and the Capillary Channel Flow (CCF) experiment. CFE-1 and CFE-2 were a suite of experiments that investigated capillary flows and flows of fluids in containers with complex geometries. CCF investigated capillary and interfacial phenomena in inertial-dominated flows. Results from these experiments are expected to improve current computer models that are used by designers of low-gravity fluid systems and lead to improved fluid transfer systems on future spacecraft.

CFE-1 consisted of a set of six separate fluid physics flight vessels that investigated capillary flows in low gravity. The CFE data is crucial to aid in design of fluid management systems including fuels/cryogen storage, thermal control, water recycling and materials processing. Under low-gravity conditions, capillary forces can be exploited to control fluid orientation so that these mission-critical systems perform predictably.

CFE-1 was a simple fundamental scientific study that yielded quantitative results. The experiments provided critical results to the capillary flow community that could not be achieved in ground-based tests, for example:

- Dynamic effects associated with a moving contact boundary condition.
- Capillary driven flow in interior corner networks.
- Critical wetting phenomena in complex geometries.

The CFE experiments included the Interior Corner Flow (ICF1, ICF2), the Vane Gap (VG1, VG2), and the Contact Line (CL1, CL2) experimental units. All units used similar fluid injection hardware, had simple and similarly sized test chambers, and relied solely on video for highly quantitative data. The test fluid was a silicone oil with viscosities selected for each unit. Other differences between units were wetting conditions and test cell cross-section. The ICF experiment investigated propellant management and passive capillary flow in tapered geometries for which boundary conditions are not well understood or modeled. The initial and secondary imbibition was investigated in two different tapering interior corner geometries. This set of experiments also tested the ability of these type of geometries to passively separate gas/liquid mixtures under low-gravity conditions. Figure 3.3-4 contains several time-sequenced images of the slow secondary imbibition in the ICF2 geometry

The VG experiment investigated the critical wetting condition when interior corners do not actually make contact, specifically the corner and gap formed by an interior vane and the interior wall of a propellant tank. The critical wetting angles have been measured to within ±0.5 degrees, nearly four times more accurate than planned. In addition, a bulk shift phenomena has been discovered that has implications for spacecraft tank design asymmetries. Figure 3.3-2 contains an image of a critical wetting angle along with a plot of experimental wetting angle results vs. theory predictions. Figure 3.3-3 contains a sequence of images of various angle positions during a complete 360-degree sweep of the vane in the test chamber.

The CL experiment studied the impact of the dynamic contact line. The contact line controls the interface shape, stability, and dynamics of capillary systems in low-g. The two CL units are identical except for their respective wetting characteristics. For the CL experiments, data from over 350 primary and extra science events have been reduced and have found significant contributions for both experimental results and numerical comparisons. The complete database can be found at http://cfe.pdx.edu. To date, the damped interface oscillations (frequency and decay) as functions of fluid properties, wetting, contact line condition, disturbance type, and amplitude have been pursued. Figure 3.3-1 provides example images of the static and dynamic states for an experimental run.

The CFE-2 is a continuation of the CFE-1 experiments and investigates increasing complex capillary flow geometries. Four re-flight units and two of the new units (ICF4 and ICF9) have been operated on ISS. The final five units have been fabricated and were scheduled to launch to ISS in June 2013.

The CCF experiment is a versatile flight experiment for studying a critical variety of inertial-capillary dominated flows and is critical to spacecraft systems that cannot be studied on the ground. The results of CCF will help innovate existing applications and inspire new ones in the portion of the aerospace community that is challenged by the containment, storage and handling of large liquid inventories (fuels, cryogens and water) aboard spacecraft. The results will be immediately useful for the design, testing and instrumentation for verification and validation of liquid management systems of current orbiting, design stage and advanced spacecraft envisioned for future lunar and Mars missions. The results will also be used to improve life support system design, phase separation and enhance current system reliability.

CCF examines flows in parallel plate channels, grooves and interior corner capillary conduits. These conduits represent a class of practical capillary geometries that are implemented in designs of spacecraft fluid processing equipment.

Validation of theoretical models developed for these geometries will increase confidence in the theory so that it may be applied to other geometries pertinent to advanced microgravity fluid systems development.

The test matrix for Experimental Unit #1, which included the parallel plate and groove channel geometries, collected over 1,300 data points with 900 consisting of high-speed, high-resolution video image (100+ GB of video data). Preliminary data analysis has verified model predictions for a number of critical conditions where the maximum flow rate occurs. In general, the measured critical flow rates for the parallel plate and groove channel were within 3 percent of each other. Preliminary results also indicate several “new” unstable conditions were discovered, which do not appear to match existing theoretical models.

Nearly 3,000 test points were collected using Experimental Unit #2, which included the wedge-channel geometry, and included high-speed and standard video imaging. Figure 3.3-5 is a video image of the critical velocity being reached during an experimental run. Data reduction has begun on the critical-flow rate data in the wedge geometry. Three preliminary flow regime maps have been generated that identify the passive gas/liquid separation regimes for the wedge channel geometry.

Further work is needed that emphasizes fluids challenges related to propellant tanks and water processing for life support. In particular, capillary-flow geometries that are tolerant to fickle wetting conditions such as that occur in spacecraft urine collection and water recycling systems, need to be further investigated. Although ground-based work is already being pursued in these newer thrust areas, the long-duration microgravity environment provided by ISS is needed for further experimental investigations such as:

- Experiments utilizing capillary flow geometries that can purposely perform passive gas/liquid phase separation.
- Capillary flow investigations that include non-isothermal effects (evaporation/condensation), normally encountered in cryogenic systems that influence wetting conditions/contact angle.
- Fundamental areas of capillary flow, investigations that utilize idealized pore geometries to gain insight into capillary wicks, water uptake in soils, etc. Testing capillary geometries of interest in micro-fluidic applications, such as for micro-scale diagnostic devices (also referred to as Lab-on-a-Chip), along with pumping and valving techniques, could be investigated before the manufacturing methods for fabricating these micro-scale features are available.

4. Opportunities for Research in Fluid Physics on ISS

4.1 Colloids and Suspensions

Fundamental studies of order, including the role of colloidal particle shape on structure and complex processes, such as self-assembly, motility and non-biological self-replication are key research areas to address using the Light Microscopy Module (LMM); adding capabilities in the future that the LMM was designed to support will enable scientists to begin controlling these important scientific frontiers in our lifetimes.

These capabilities include: (1) a faster frame rate for constructing 3-D confocal images quickly with a higher-resolution, low-noise Complimentary Metal-Oxide Semiconductor color camera that is radiation tolerant on ISS. Scientists are beginning to observe new and interesting behaviors when the frame-rate goes above 100 frames-per-second; (2) particle and cluster manipulation capabilities using dynamic laser tweezers that allow scientists to manipulate samples and to introduce defects to see and understand how nature heals. Dynamic laser tweezers will also enable scientists to grow ordered structures from patterned layers that can be laid down by the laser tweezers, patterns whose spacing can also be manipulated in this way. This will enable scientists to see what nature prefers and how to best coax her when another structure or pattern is needed to realize a needed technology; (3) homodyne dynamic light scattering to measure particle diffusion coefficients in regular sample cells and in temperature gradient cells (to provide phase diagram location and translational and rotational diffusion coefficients); (4) spectrometry capabilities for quantifying new colloidal crystals and their growth rates. This will be useful for things like seeded growth studies where growth rates and other properties of homogeneous and controlled heterogeneous crystals can be compared; (5) variable crossed-polarizers for quantifying the polarization rotation predicted for liquid crystals and new types of materials; and (6) a vibration cancelling three-axes Piezo-platform for holding samples that will significantly improve submicron imaging and 3-D confocal image sectioning and image reconstruction.

4.2 Liquid Crystals (Structures and Dynamic Studies)

An important area of soft condensed matter physics and chemistry that has been making major discoveries and rapid advancement and immediate applications in the consumer electronics is study of liquid crystal. Increased understanding of the dynamics, morphology and structures of liquid crystals significantly enhance the ability to control the properties of this type of complex fluid. Liquid crystals are incredibly important as a fundamental material for modern display and information storage and processing technologies as well as possible high-efficiency energy conversion devices.

The structural study of growth behavior of domains on liquid crystals commonly known as islands and holes on liquid crystal monolayers and thin freely suspended films is an area of interest in the understanding of growth behavior, long- and short-time growth studies and the experimental verification of growth models like reverse aggregation, universal growth law. While much work has been done in understanding the growth kinetics process in other systems like crystallization and the phase separation of binary alloys, only recently has the phase ordering process been studied in systems that form liquid crystals. Systems that form liquid crystal are a good candidate for studying phase ordering kinetics since they can be directly observed by Depolarized Reflective Light Microscopy, which will be available in the very near future aboard ISS fluid facilities.

4.3 FOAM

Foams can be categorized under soft condensed matter in different form as they are dispersions of gas into liquid or solid matrices. They are typically made in conditions where the matrix is liquid. The behavior of foams in microgravity and on Earth are very different because the process of drainage is absent in microgravity conditions. The irreversible flow of liquid through the foam deform to polyhedra throughout the foam, creating the so-called “dry foam”. As the foam bubbles get to the critical thickness/thinness, it eventually breaks, and the foam collapses. This happens when suitable stabilizing agents are absent (well-chosen surfactants or solid particles for aqueous foams). Microgravity offers the opportunity to investigate the so-called “wet” foams, which cannot be stabilized on Earth, because of drainage problem. Theoretical approaches of drainage rely on assumptions, which are only valid for dry foams. New behaviors or regimes are expected to appear for wet foams, masked by convective instabilities on Earth. Elastic and viscous properties of wet foams are also expected to be strongly modified by the presence of solid particles and the physics of wet foams is, therefore, poorly known.

Future work on foam related to current trends in this area is to explore wet foams beyond the limits imposed by the different instabilities occurring under normal gravity conditions, such as the convective instability. The results of these studies will serve to better characterize the normal-gravity instabilities to the extent that foam processing industry can be controlled and further optimized. This improves foam control or process design with respect to what is currently available on the basis of necessarily conservative empiricism.

4.4 Granular Materials

Granular matter is the most common and pervasive medium besides air and water, yet the understanding of its statics and dynamics lags significantly behind that of conventional solids and fluids. This is because rationally derived constitutive relations do not exist between strain (or strain rates) and the stresses in granular media. Lacking these relations, the ability to predict the dynamics of granular materials and to design the associated equipment is severely limited.

Granular Materials research is currently not funded by NASA. To develop this critical area, a ground-based program must be funded to develop the pool of future ISS researchers. In our proposed set of experiments we would start with a set of two successive ISS flight experiments to develop and test models for both static (jammed) and dynamic (flowing) states. In parallel, a ground-based and eventually a flight experiment would be developed to conduct simulated "icy regolith" flows where the effects of ice and water on material handling will be studied.

4.5 Particulate Management

Particulate (dust) management will be crucial in ensuring healthy, habitable conditions on future manned missions. An effective dust management plan implemented over the course of these missions will minimize the buildup of particulate matter in the transit vehicle and inside the surface habitats, and mitigate against its deleterious effects. Dust can have varying effects on system components. It can degrade the movement of mechanical parts, penetrate seals, obscure optical surfaces (e.g., windows) and sensors, and short out electronic components. Airborne or suspended micron and sub-micron size particles are particularly problematic since their persistence in large concentrations can pose acute health problems. Unchecked micro-organisms can lead to microbial and other mold growth, which will also impact crew health.

The fundamentals of aerosol transport are well known for terrestrial applications. However, the indefinite residence times in transit vehicles and orbitals—e.g., ISS—notwithstanding, the dust capturing that takes place in the ventilation and filtration systems leads to extended particle-particle interactions. Areas of poor ventilation or flow stagnation regions will be more susceptible to dust buildup. A detailed look at these mechanisms under the microgravity environment and large aggregate loading conditions will provide valuable engineering information on the best approaches for dust capturing controls. These can include investigations of the fibrous capturing mechanisms, impaction, interception and diffusion, and alternate approaches such as inertial, electrostatics and surface/fiber coatings. The added effects of the reduced pressure environments will also factor in. Two ISS experiments are recommended to study these effects as well as test techniques to effectively remove dust particles in the ISS environment.

4.6 Magnetorheological Fluids

MR suspensions are normally stable, fluid suspensions that will undergo a dynamic mechanical transition to a solid within milliseconds after the application of an external magnetic field. This rapid and reversible transition in the material mechanical behavior is due to the distinct microstructural transition in the fluid driven by the polarization of particles. The mechanical energy required to strain and disrupt such networks leads to elasticity and yielding, but the suspension reverts to liquid-like behavior almost immediately after removing the field.

MR fluids provide the basis for technologies ranging from actively controlled dampers and actuators to magnetically sealed bearings and sensitive stress transducers. Applications in space exploration include their potential use in robots, rovers and crew suits (mobility augmentation), especially for endurance and fatigue countermeasure designs that aid in lifting, moving and supporting loads during extra-vehicular activities (EVAs or spacewalks). In addition to their immediate applications in mechanical systems, MR suspensions have become important components in microfluidic devices that could lead to compact medical instrumentation and diagnostics for Earth-based and long-duration spaceflight applications.

4.7 Polymer Fluids

The combination of both shearing and extensional flows is common in many polymer processing operations such as extrusion, blow-molding and fiber spinning. Therefore, knowledge of the complete rheological properties of the polymeric fluid being processed is required in order to accurately predict and account for its flow behavior. In addition, if numerical simulations are to serve as a priori design tools for optimizing polymer processing operations, then it is critical to have an accurate knowledge of the extensional viscosity and its variation with temperature, concentration, molecular weight, and strain rate.

4.8 Multiphase Flows

The gas-liquid interface is the focus of multiple phenomena involving interactions among bubbles, drops and solid objects. It is also the boundary across which momentum, mass and heat transfer occur. Although studies have been conducted on the interactions of the interface in reduced gravity, most careful measurements have been made with limited systems consisting of only a handful of bubbles and drops and have not been complicated by bulk fluid motion and phase change. The results of these studies are not sufficient to develop predictive models to describe multiphase flow behavior in microgravity.

Phase density and interfacial tension dominate the behavior of multiphase systems in reduced gravity unlike that in normal gravity. While phase density in normal gravity results in a buoyancy-driven segregation of the phases and distorts the shape of the interface, the impact of the phase-density difference is primarily evident in the flow momentum, which is demonstrated by the flow distribution in splitting tees and cyclonic separators. Interfacial tension in reduced gravity causes the gas-liquid interface to become more spherical at larger length scales. It is necessary to develop a fundamental understanding of multiphase flow behavior and of the momentum, heat and mass transfer processes in microgravity. Discrete critical parameters should be measured experimentally to develop and validate predictive models. These models are essential tools needed by designers of life support, propulsion, power and other systems for use in space and on the moon and Mars.

It is necessary to examine Two Phase Flow Instability Mechanisms. These mechanisms are heavily influenced by the gas/vapor phase density and its compliance (Ledinegg Instability) to system controls such as pressure control systems, pump characteristics, etc. Phase distribution in manifolds for parallel channel evaporators and condensers will be governed by both phase momentum and interfacial phenomena.

4.9 Thermocapillary and Solutocapillary Flow Phenomena

Many multiphase flow phenomena in reduced gravity are driven by variations in surface tension caused intentionally or inadvertently because of gradients in temperature, concentration or wetting conditions. Such flows, also called thermocapillary/solutocapillary flows or Marangoni convection, find application in most fluid systems in space such as propellant management systems, thermal control systems, cryogenic fluid systems, life support systems, etc. Fluid systems in which bubbles, drops and nucleation phenomena occur are particularly susceptible to flows driven by surface tension gradients.

4.10 Capillary Flow Phenomena

Capillary flows and phenomena are applicable to a myriad of fluids management systems in low-g including fuel and cryogen storage systems, thermal control systems (e.g., vapor/liquid separation), life support systems (e.g., water recycling), and materials processing in the liquid state. In fact, NASA's near-term exploration missions plan larger liquid propellant masses than have ever flown on interplanetary missions. Under microgravity conditions, capillary forces can be exploited to control fluid orientation so that such large mission-critical systems perform predictably.

5. Lessons Learned

The NASA Colloids program has caused several paradigm shifts in soft condensed matter physics. These include observations of the disorder to order transition (glasses on Earth crystallizing in microgravity), crystallization arresting phase separation, model critical fluids having critical points far from where theory predicted them to be, bi-disperse systems showing unexpected behaviors (particle stabilizer particles that are 20 percent smaller are not forming clusters in the presence of dilatant attractants in the same way as their larger siblings), the presence of seed particles affecting the type of nucleation being observed.

Analysis of the experimental data revealed interesting elastic instabilities on the free surface of the fluid sample. The data showed the formation of beads-on-a-string structures in the absence of gravitational sagging. The development and evolution of such phenomena upon cessation of elongation have not yet been described.

The design of a heat transfer experiment should account for extreme heating without impacting the bulk fluid temperature of a fluid. Consequently, heater temperatures should be measured directly and incorporated into control/protection circuit and these heaters and other convective heat devices should be derated from normal to microgravity operation. The electrical system of any experiment should be designed so failed components can be isolated in order to maintain maximum capabilities in the event of a failure by individually fusing heaters and use independent controls to activate/deactivate them.

Complexity of the experiment should be minimized if at all possible. Science requirements that add complexity not only add additional cost to the development, but often lengthen the development time, making turnover an issue for both the project team and, in particular, for the principal investigator (PI) and his/her science team when the experiment timeline extends beyond the typical tenure of a Ph.D. student. Design the experiment to be flexible and repairable. Unlike the space shuttle experiment days, the ISS has become more like a laboratory on Earth where the crew members often gain rather good experimental skills while operating a particular experiment over months rather than a week or so, and can become quite adept at experiment repair if this capability is designed into the experiment and clear straightforward procedures are provided.

6. ISS Facilities for research of Fluid Physics

6.1 Acceleration Measurement and Environment Characterization

Space Acceleration Measurement System (SAMS) and Microgravity Acceleration Measurement System (MAMS) provide continuous measurement of the ISS vibratory and quasi-steady acceleration environment, respectively. SAMS measurement capability extends to all three laboratories, while MAMS data can be mathematically mapped to any arbitrary location using rigid-body assumptions.

SAMS and MAMS support NASA's Physical Sciences Research Program. These systems along with Principal Investigator Microgravity Services analysis serve a critical, ongoing role in support of vehicle/loads monitoring. SAMS and MAMS monitor vehicle dynamic loads and assist technology developers and principal investigators in various disciplines. The goal is to characterize and understand the acceleration environment as related to a wide array of disturbances and events that routinely or uniquely take place on the ISS.

6.2 Fluids Integrated Rack (FIR)

The FIR was designed to test and understand critical technologies needed for advanced life support and future spacecraft thermal control, research in complex fluids (colloids), and life science experiments. The hardware was delivered on STS-128 (August 2009) to the ISS and installed in the Fluids and Combustion Facility of the U.S. Lab. The FIR contains the hardware and software necessary for conducting fluid physics science experiments. It is designed to accommodate a range of fluids experiment while meeting the ISS requirements and limitations such as safety, power and energy, cooling, mass, crew time, stowage, resupply flights, and downlink. The FIR utilizes six major subsystems to accommodate the broad scope of fluids physics experiments. The major FIR subsystems are structural, environmental, electrical, gaseous, command and data management, and diagnostics. These subsystems combined with payload-unique hardware allow the FIR to conduct world-class science. It also provides the largest, contiguous volume for experimental hardware of any ISS facility, easily reconfigurable diagnostics, customizable software, active rack-level vibration isolation and other subsystems required to support a wide range of gravity-dependent fluid physics and life science investigations. The Light Microscopy Module (LMM), or microgravity microscope, is an integral part of this facility.

6.3 Light Microscopy Module (LMM)

The LMM is a remotely controllable in-orbit microscope subrack facility, allowing flexible scheduling and control of physical science and biological science experiments within NASA's Glenn Research Center FIR on the ISS. The LMM concept is a modified commercial research imaging light microscope with powerful laser-diagnostic hardware and interfaces, creating a one-of-a-kind, state-of-the-art microscopic research facility. The microscope will house several different objectives, corresponding to magnifications of 10x, 40x, 50x, 63x, and 100x. Features of the LMM include high-resolution, color video microscopy, bright field, darkfield, phase contrast, differential interface contrast (DIC), spectrophotometry, and confocal microscopy combined in a single configuration. Laser tweezers, a sample manipulation technique, is integrated with the diagnostics. The LMM provides an enclosed work area called the auxiliary fluids container with glove ports and an equipment transfer module for transporting experiment samples from stowage to the LMM.

6.4 (MSG)

The Microgravity Science Glovebox (MSG) is a research facility installed on the ISS in which fundamental and applied scientific research is conducted in support of the NASA Headquarters' Vision for Space Exploration. This facility was designed to accommodate small science and technology experiments in a "workbench" type environment. Because the facility's working volume is enclosed and held at a negative pressure with respect to the crew living area, the requirements on the experiments for containment of small parts, particulates, fluids and gases in the low-gravity space station environment are substantially reduced. The concept allows scientific flight hardware to be constructed in close parallel with bench experiments developed in ground-based laboratories. The facility is ideally suited to provide quick accommodations for exploration investigations that are necessary to gain an initial understanding on the role of gravity in the physics associated with new research areas.

Research investigations operating inside the MSG are provided a large, 255-liter enclosed work space, 1,000 watts of dc power via a versatile supply interface (120, 28, +12, and 5 Vdc), 1,000 watts of cooling capability, video and data recording and real-time downlink, ground commanding capabilities, access to ISS Vacuum Exhaust and Vacuum Resource Systems, and gaseous nitrogen supply. These capabilities make the MSG one of the most utilized science facilities on the ISS. In fact, the MSG has been used for over 10,000 hours of scientific payload operations. MSG investigations involve research in cryogenic fluid management, fluid physics, spacecraft fire safety, materials science, combustion, plant growth, human health and life support technologies. The MSG facility is ideal for advancing our understanding of the role of gravity upon science investigations and research, and to utilize the ISS as a technology platform for space exploration.

6.5 EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Racks

The eight EXPRESS racks are multi-use facilities, which provide standard interfaces and resources for Middeck Locker and International Subrack Interface Standard drawer payloads. Payloads using single-, double- or quad-locker and/or drawer configurations can be accommodated by these racks. The racks provide a number of services for payloads including Nitrogen, Vacuum, RS422, ethernet, video, air and water-cooling.

7. Developing and flying Fluid Physics research to ISS

The research community will be provided specific research topics through NASA Research Announcements. In response the research community will generate ideas regarding the topics and submit them to NASA. NASA will evaluate the response and make selections through a peer review process. Awards will then be granted for ground-based research at NASA and/or PI institutions. PIs will be required to successfully pass the Science Concept Review and Requirements Design Review. Flight research experiment concepts and designs will undergo the Preliminary Design, Critical Design, and System Acceptance Review processes before launching fluids physics research and operating on the ISS.

8. Funding Opportunities / Points of Contact

NASA Headquarters will provide the information.

9. Citations:

Bailey, A. E., W. C. K. Poon, R. J. Christianson, A. B. Schofield, U. Gasser, V. Prasad, S. Manley, P. N. Segre, L. Cipelletti, W. V. Meyer, M. P. Doherty, S. Sankaran, A. L. Jankovsky, W. L. Shiley, J. P. Bowen, J. C. Eggers, C. Kurta, T. Lorik, Jr., P. N. Pusey, and D. A. Weitz, "Spinodal Decomposition in a Model Colloid-Polymer Mixture in Microgravity," *Physical Review Letters 99*, 205701, 2007.

Cheng, Z. D., J. X. Zhu, W. B Russel, W. V. Meyer, P. M. Chaikin, "Colloidal Hard-sphere Crystallization Kinetics in Microgravity and Normal Gravity," *Appl. Optics 40*, pp. 4146-4151, 2001.

Manley, S., Benny Davidovitch, Neil R. Davies, L. Cipelletti, A. E. Bailey, R. J. Christianson, U. Gasser, V. Prasad, P. N. Segre, M. P. Doherty, S. Sankaran, A. L. Jankovsky, B. Shiley, J. Bowen, J. Eggers, C. Kurta, T. Lorik, and D. A. Weitz, "Time-Dependent Strength of Colloidal Gels," *Physical Review Letters 95*, 048302, 2005.

Manley, S., L. Cipelletti, V. Trappe, A. E. Bailey, R. J. Christianson, U. Gasser, V. Prasad, P. N. Segre, M. P. Doherty, S. Sankaran, A. L. Jankovsky, B. Shiley, J. Bowen, J. Eggers, C. Kurta, T. Lorik, and D. A.Weitz, "Limits to Gelation in Colloidal Aggregation," *PRL 93,* 108302, 2004.

Yunker, P. J., T. Still, M. A. Lohrand A. G. Yodh, “Suppression of the Coffee-ring Effect by Shape-dependent Capillary Interactions,” *Nature,* 476, 2011.

Juan Sabin, Arthur E Bailey, Gabriel Espinosa, Barbara J Frisken, Physical Review Letters. 11/2012; 109:195701.

Wang, Ton, Ruojie Sha, Rémi Dreyfus, Mirjam E. Leunissen, Corinna Maass, David J. Pine, Paul M. Chaikin, and Nadrian C. Seeman, “Self-replication of Information-bearing Nanoscale Patterns,” *Nature 478*, October 13, 2011.

Yunker, P.J., K. Chen, Z. Zhang, and A. G. Yodh, "Phonon Spectra, Nearest Neighbors, and Mechanical Stability of Disordered Colloidal Clusters with Attractive Interactions," *Physical Review Letters 106*, 225503, 2011.

Chato, D. J., and Martin, T. A., “Vented Tank Resupply Experiment Flight Test Results,” *NASA TM 107498, AIAA-97-2815*, 1997

Bentz, M. D., Albayyari, J. M., Knoll, R. H., Hasan, M. M., and Lin C. S., “Tank Pressure Control Experiment: Results of Three Space Flights,” *AIAA-97-2816*, 1997.

Merte, H., Lee, H. S. and Keller, R. B., “Dryout and Rewetting in the Pool Boiling Experiment Flown on STS-72 (PBE-II B) and STS-77 (PBE-II A),” *NASA/CR--1998-207410*, 1998.

Raj, R., Kim, J., and John McQuillen, “Pool Boiling Heat Transfer on the International Space Station: Experimental Results and Model,” *Journal of Heat Transfer*, Vol. 134, (2012).

Dhir, V. K., Warrier, G. R., Aktinol, E, Chao, D., Eggers, J., Sheredy, W., and Booth, B., “Nucleate Pool Boiling Experiments (NPBX) on the International Space Station*,” Microgravity Sci. Technol.* (2012) 24:307-325.

Cantwell, E .R. and W. M. Kohrt, “Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era,” *Committee for the Decadal Survey on Biological and Physical Sciences in Space, Research, Space Studies Board, National Research Council,* Washington, DC, 2011.

Voorhees, P. W., “Assessment of Directions in Micro–gravity and Physical Sciences Research at NASA,” *Committee on Microgravity Research, National Research Council*, Washington, DC, 2003.

Viskanta, R., “Microgravity Research in Support of Technologies for the Human Exploration and Development of Space,” *Committee for Micro–gravity Research, Space Studies Board, National Research Council,* Washington, DC, 2000.

Lahey Jr., R. T., and V. Dhir “Research in Support of the Use of Rankine Cycle Energy Conversion Systems for Space Power and Propulsion,” *NASA/CR—2004-213142,* 2004.

Chiaramonte, F. P., and J. A. Joshi, “Workshop on Critical Issues in Microgravity Fluids, Transport, and Reaction Processes in Advanced Human Support Technology,” *NASA/TM—2004-212940,* 2004.

Petrash, D. A., Zappa, R. F., Otto, E. W., “Experimental Study of the Effects of Weightlessness on the Configuration of Mercury and Alcohol in Spherical Tanks, *NASA Technical Note D-1197*, 1962.

Petrash, D. A., Nussle, R. C., Otto, E. W., “Effect of the Acceleration Disturbances Encountered in the MA-7 Spacecraft on the Liquid-Vapor Interface in a Baffled Tank During Weightlessness”, *NASA Technical Note D-1577*,1963.

Siegel, R., “Transient Capillary Rise in Reduced and Zero-Gravity Fields”, *J. Appl. Mech.* 28(2), 165,1961.

Chen, Y., Tavan, N., Weislogel, M.M., “A mean curvature model for compound capillary flows in asymmetric containers and conduits”, *Physics of Fluids*, Vol. 24, 082111, 2012.

Weislogel, M.M. “Compound Capillary Rise,” *J. Fluid Mech.*, Vol. 709, 2012.

P.J. Canfield, P.M. Bronowicki, Y. Chen, L. Kiewidt, A. Grah, J. Klatte, R. Jenson, W. Blackmore, M.M. Weislogel, M.E. Dreyer, “The Capillary Channel Flow Experiments on the International Space Station: Experiment Setup and First Results”, *Exp. Fluids*, 54:1519, 2013.

Haake, D., Klatte, J., Grah, A., Dreyer, M. E., “Flow rate limitation of steady convective dominated open capillary channel flows through a groove,” *Microgravity Sci. Tech.* 22, 2010.

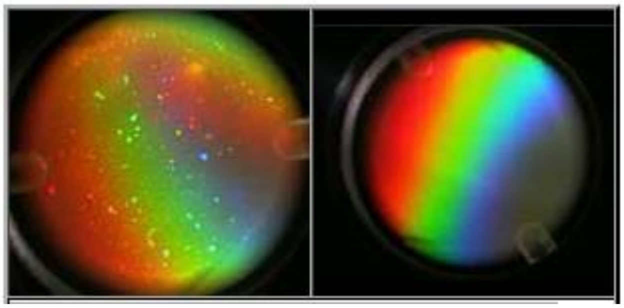


Figure 3.1-1: Ground vs. space:

The two PCS photos above are of white light shown through binary alloy samples (D. A. Weitz, et al.). The left sample was grown on the ground and the right sample (sample AB6) was grown on the International Space Station during Increment 2. The different colors are the result of different wavelengths of light being diffracted by the crystal nuclei, indicating the ordered placement of particles in the suspension. A sharply defined spectrum reveals a highly ordered particle placement in the colloidal suspension.

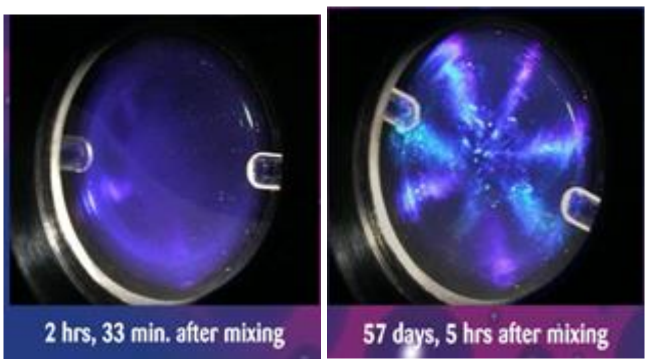


Figure 3.1-2: Investigations conducted by Physics of Colloids In Space principal investigators (P. M. Chaikin, et al.) have yielded some unexpected and pleasantly surprising results: solutions that formed glasses on Earth formed crystals and dendritic growth in space; and nucleation and growth that was anticipated by preliminary studies but never observed during the crystal growth process.

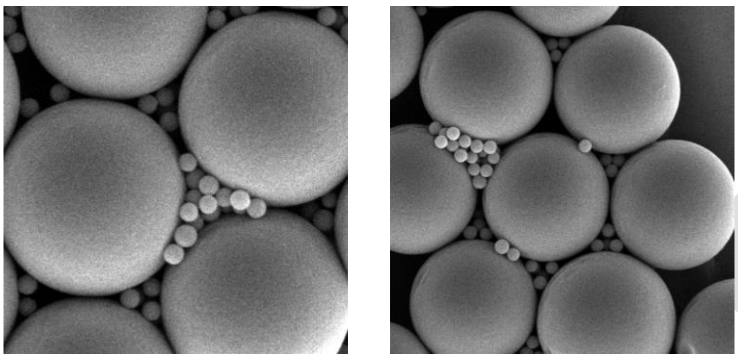


Figure 3.1-3: SEM images of a mixture of 3.8 micron diameter "seed" particles together with the bulk colloid (0.33 micron diameter PMMA spheres). Crystal nucleation on the spherical surfaces could produce small nuclei that grow radially outward. Because of curvature that makes it difficult to maintain an unstrained structure, they should detach from the surface, allowing the seed to produce new crystal nuclei.

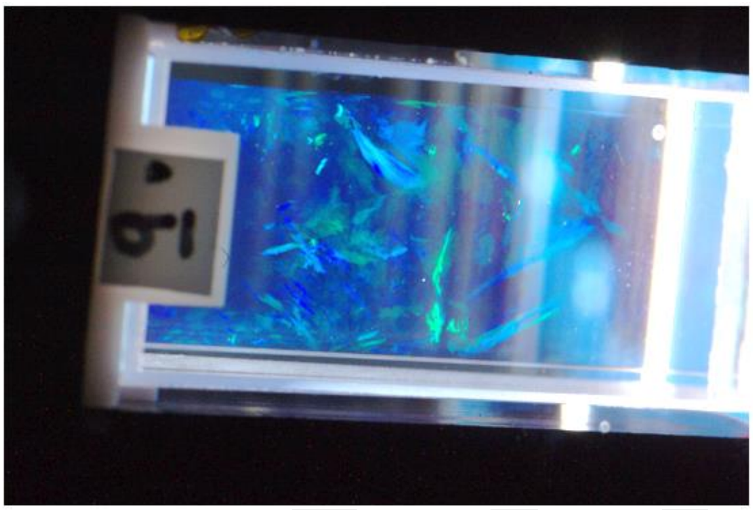


Figure 3.1-4: Controlling heterogeneous nucleation. Binary Colloidal Alloy Tests-5 flight experiment, sample 9 on ISS. Colloidal glass with seed particles crystallize in microgravity. Microgravity allows scientists to study this mechanism without the complicating effects of particle sedimentation.

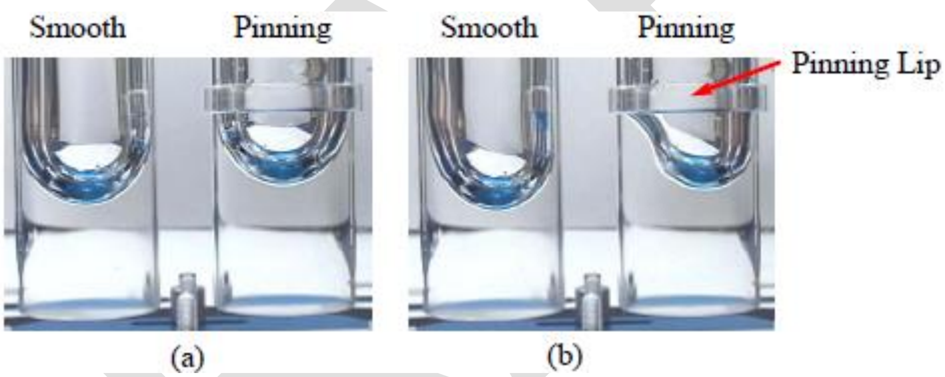
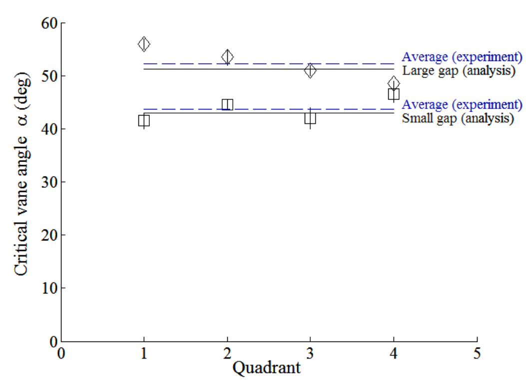


Figure 3.3-1: Image of Contact Line 2 showing smooth and pinning edge boundary conditions under (a) equilibrium, and (b) dynamic states.



(a) **(b)**

Figure 3.3-2: (a) Science image of the Capillary Flow Experiments Vane Gap-1 vessel at a 45° vane angle. A large “finger” of fluid has filled the gap between the vane and chamber inside the surface closest to the camera view at the critical angle of 45 degrees (within ±1.5 degrees of predicted value); (b) Test points like this one provide experimental verification of present analytic and numerical methods to predict such nearly discontinuous static and dynamic phenomena.

Figure 3.3-3: Equilibrium interfaces for Vane Gap-1 for several vane dial angles: 0, 36, 43, 53, 59.5, 90, 127.5, 134.5, 150.5, 180 degrees (from top left to bottom right).

Figure 3.3-4: Image sequence of Interior Corner Flow2 bubble migration where each image is approximately 60 seconds apart. The bubble location measurements, z_1 and z_2, are tracked and compared with analytic and numeric predictions.

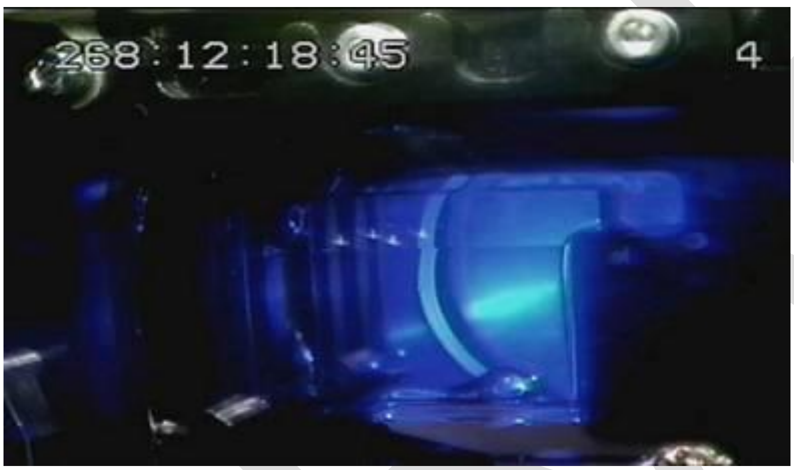


Figure 3.3-5: Capillary Channel Flow image of Experimental Unit #2 using second Microgravity Science Glovebox camera. Bubble in lower portion of image indicates the critical flow rate has been reached for this test point.

ACRONYMS

BCAT	Binary Colloidal Alloy Tests
BDB	Buoyancy Dominated Boiling
CCF	Capillary Channel Flow
CFE-1, CFE-2	Capillary Flow Experiments
CL1, CL2	Contact Line
EXPRESS	EXpedite the PRocessing of Experiments to Space Station
FIR	Fluids Integrated Rack
FOAM	Foam Optics And Mechanics
ICF1, ICF2	Interior Corner Flow
ISS	International Space Station
LMM	Light Microscopy Module
MABE	Microheater Array Boiling Experiment
MAMS	Microgravity Acceleration Measurement System
MR	Magnetorheological
MSG	Microgravity Science Glovebox
NPBX	Nucleate Pool Boiling eXperiment
PBE	Pool Boiling Experiments
PCS	Physics of Colloids in Space
PI	Principal Investigator
PMD	Propellant Management Devices
SAMS	Space Acceleration Measurement System
VG1, VG2	Vane Gap
VTRE	Vented Tank Resupply Experiment